The broad-band X-ray spectrum of the Cas A supernova remnant as seen by the BeppoSAX observatory

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Abstract. We present a broad band X-ray observation of the Cas A supernova remnant, obtained with the 4 narrow field instruments on board the BeppoSAX satellite. The X-ray spectrum thus obtained spans more than two decades in energy, from $\simeq 0.5$ to $\simeq 80$ keV. The complete spectrum is fit with a two-component non-equilibrium ionization (NEI) model plus a power-law component which dominates at the higher energies. The influence of the hard X-ray tail on the parameters derived for the thermal emission is discussed.

Key words: ISM: abundances; ISM: individual objects: Cas A: ISM: supernova remnants: X-rays: ISM

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1. Introduction

The remnants of many supernova explosions are bright X-ray sources, with their soft X-ray spectra showing strong metal emission lines, and characteristic temperatures ranging from below 1 keV up to a few keV. Thanks to their high X-ray luminosity and their complex spectra, they have been a frequent target for spectroscopic X-ray observations. Of particular interest are the remnants in which the ejected remains of the parent supernova are visible in the optical and are recognizable from their very high metal abundance, a class for which the Cas A remnant is often considered the prototype. X-ray emission is in these systems modeled as being due to two distinct plasma components, i.e. the ejecta from the supernova explosion, heated to X-ray temperatures by the reverse shock, and the shocked surrounding circumstellar medium (CSM), heated by the forward shock ploughing through it. In this simplified view, the two components are expected to have different characteristics, with the ejecta very metal rich, and with abundance values reflecting the results of the nucleosynthesis which took place in the supernova progenitor as well as in the explosion itself. At the same time, the emission from the shocked CSM should show abundance values resulting from a mix of the interstellar medium and of the stellar wind from the progenitor. Analysis of the X-ray spectrum can thus be used to derive an estimate of the mass of the shocked material, for both emission components, as well as the metal abundance and the mass fraction of each element in the ejecta. These parameters can be used to directly verify models of nucleosynthesis in supernova progenitors.

Given the young age of the Cas A remnant ($\simeq 320$ yr) the shocked plasma is not expected to have reached ionization equilibrium, and indeed it is by now accepted that the X-ray emission of supernova remnants is better modeled with non-equilibrium ionization (NEI) plasma emission codes than with codes modeling the emission of a plasma in collisional equilibrium.

At the same time, hard X-ray emission of non-thermal origin has been detected in some of these remnants, extending to energies of $\gtrsim 100$ keV. Such a hard X-ray tail is of course of astrophysical interest by itself, and it is also important since it contributes to the soft X-rays, thus biasing the interpretation of the thermal emission (The et al. 1996).

The X-ray satellite BeppoSAX (Boella et al. 1997a) includes four co-aligned Narrow Field Instruments, with complementary energy band coverage, ranging from 0.1 to $\gtrsim 100$ keV: the Low Energy Concentrator Spectrometer (LECS, Parmar et al. 1997), the three Medium Energy Concentrator Spectrometers (MECS, Boella et al. 1997b), the High-Pressure Gas Scintillation Proportional Counter (HPGSPC, Manzo et al. 1997) and the Phoswich Detector System (PDS, Frontera et al. 1997).

Given both its astrophysical interest, and its usefulness as a calibration source, Cas A was included as a target in the Science Verification Phase (SVP) of the BeppoSAX program. During the SVP Cas A was observed at different times. In the
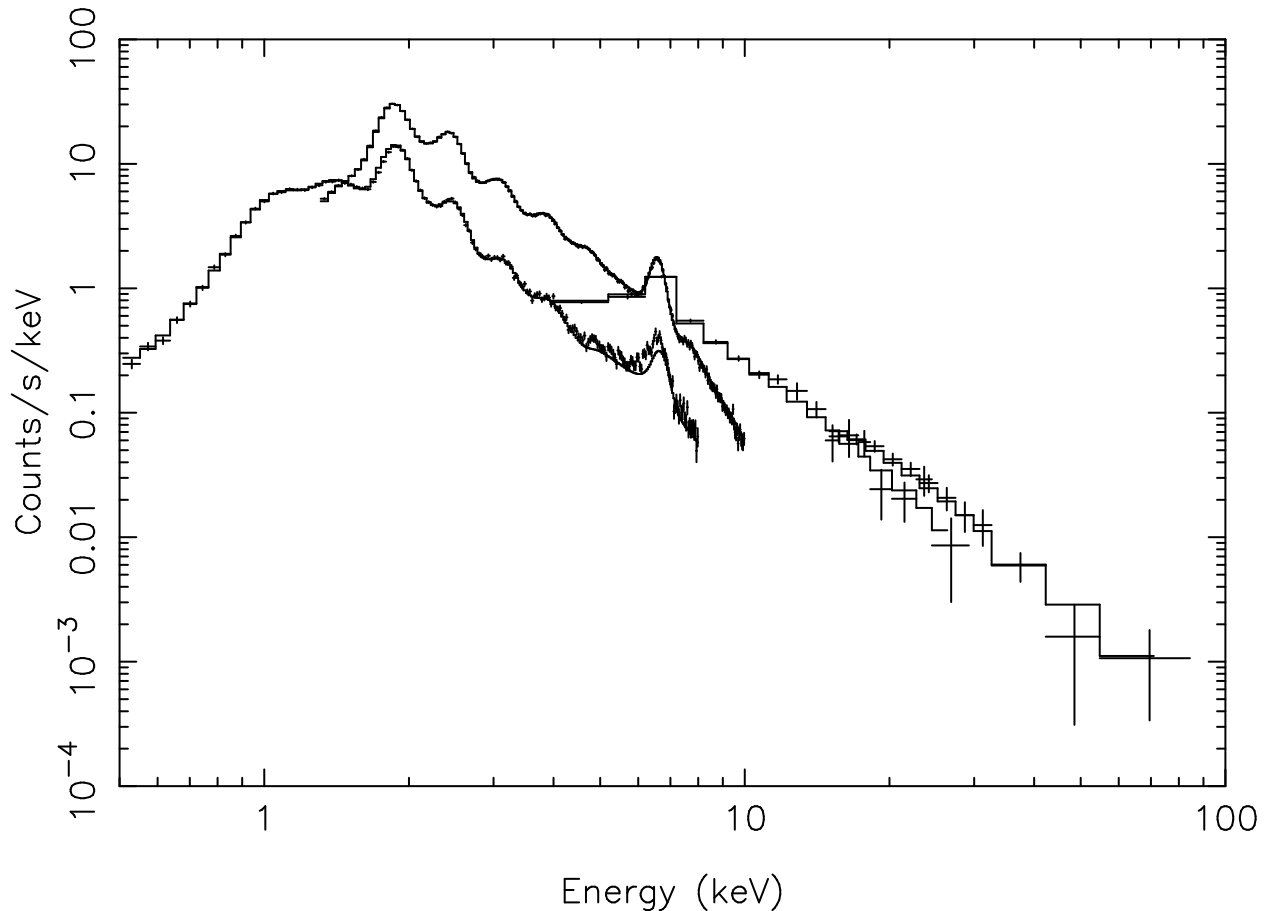
Fig. 1. The observed composite BeppoSAX spectrum of Cas A, using data from the LECS, MECS, HPGSPC and PDS instruments, together with the best-fit two-component NEI plus power-law model.

present paper we discuss the spatially-integrated broad-band spectrum of Cas A, obtained using all the narrow-field instruments on board the BeppoSAX satellite. In the present paper the LECS data have been used to cover the spectral range 0.5–8.0 keV, the MECS data the range 1.5–10 keV, the HPGSPC data the range 5.0–30 keV and the PDS data the range 20–80 keV. While the LECS is sensitive down to 0.1 keV, interstellar absorption is such that no source flux is detected below $\simeq 0.5$ keV.

2. Analysis

The Cas A remnant is several arcmin in size, and thus is, at the resolution of the LECS and MECS detectors ($\simeq 1$ arcmin), an extended source. In the present paper however only the spatially integrated spectrum of the remnant is discussed. The data analysis was performed using the SRON SPEX package, following an approach similar to the one adopted by Vink et al. (1996) — VKB in the following — who analyzed the Cas A X-ray spectrum from the ASCA SIS. The source spectrum was modeled by two distinct NEI components, one representing the

emission from the ejecta, the other from the shocked CSM. In our model the CSM component is assumed to be the hotter one, and the emission from the ejecta is modeled as the cooler component of the spectrum[1]. In addition, a third component is used, in the form of a power-law, to model the hard X-ray emission. The power-law component is assumed to extend across the whole X-ray spectrum, i.e. no cut-off was imposed. The distance to the SNR was assumed to be 3.4 kpc (Reed et al. 1995).

Given the current residual absolute calibration uncertainties of the various BeppoSAX instruments, the relative normalization of the different data sets has been considered as a free parameter, using the MECS normalization as reference. In practice the LECS and PDS normalizations agree well with each other, as do the MECS and HPGSPC ones. The LECS/PDS normalization is $\simeq 25\%$ lower than the MECS/HPGSPC one, in agreement with the values found for other SVP sources.

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[1]   An alternative temperature structure has been proposed by Borkowski et al. (1996), who attribute the cool thermal emission to the CSM and the hot emission to the ejecta.

Table 1. The best-fit parameters for the adopted two-component NEI plus power-law model to the Cas A BeppoSAX spectrum. The range between brackets is the formal 90% range ($\Delta\chi^2 = 2.71$). The entries in the "VKB" column are averaged values from the analysis of the ASCA SIS spectrum of VKB.

Element	SAX	VKB
Ejecta component		
$n_e n_H V$ (10^{62} m^{-3})	0.45 [0.36–0.64]	2.5
Post-shock T (keV)	1.25 [1.20–1.33]	0.7
$n_e t$ (10^{15} m^{-3}s)	62 [57–68]	170
CSM component		
$n_e n_H V$ (10^{62} m^{-3})	83 [68–93]	270
Post-shock T (keV)	3.8 [3.5–4.2]	4.2
$n_e t$ (10^{15} m^{-3}s)	188 [165–220]	130
global abundance	9.6 [7.5–12]	3.5
Power-law component		
Norm. (10^{44} ph s^{-1} keV^{-1} at 1 keV)	9.7 [8.8–10.7]	–
Photon index	2.95 [2.90–3.04]	–
Interstellar absorption		
N(H) (10^{22} cm^{-2})	1.22 [1.19–1.26]	1.5

Table 2. The mass fraction, relative to oxygen, implied by the best-fit NEI model for the ejecta. The range indicated within the brackets is the formal 90% range (i.e. $\Delta\chi^2 = 2.71$). The entries in the "VKB" column are averaged values from the analysis of the ASCA SIS spectrum of VKB, while the ones in the "JY84" column are the theoretical calculations from Johnston & Yahil (1984).

Element	SAX	VKB	JY84
Ne	0.000 [0.000–0.010]	0.02	0.327
Mg	0.015 [0.011–0.019]	0.006	0.077
Si	0.100 [0.070–0.130]	0.04	0.092
S	0.069 [0.046–0.079]	0.03	0.036
Ar	0.020 [0.014–0.026]	0.01	0.006
Ca	0.020 [0.013–0.024]	0.01	0.006
Fe	0.025 [0.021–0.033]	0.02	0.15
Ni	0.026 [0.021–0.031]	0.003	–

Given the complexity of the model we have used and thus the large number of parameters, not all the parameters can be derived from the data by a blind fitting procedure. Some choices have been made a priori based on the current physical understanding of the source. The parent supernova is thought to be a helium star, which had shed all of its hydrogen envelope, and indeed the optical spectrum of the ejecta indicates that they are essentially devoid of hydrogen and rich in oxygen. We simulate this, in our ejecta model, by imposing a very high, fixed oxygen abundance relative to hydrogen, and thus determining the abundance of the other elements *relative to O*. The O abundance has been fixed to 10^4 times solar, but the results are not sensitive to the precise value used (i.e. a value of 10^2 or 10^3 would yield very similar results). For the ejecta component, in addition to the normalization, the post-shock temperature and

the ionization time, the abundance of all individual elements (Ne, Mg, Si, S, Ar, Ca, Fe, Ni) is initially left free to vary. One additional parameter is the abundance of the lighter elements relative to oxygen. He, C and N have no measurable line emission due to the strong absorption, yet the value of their abundance (specially C) in the ejecta is important because they contribute to the continuum emission. Thus, more carbon yields a higher continuum and thus lower abundance for the other elements. Therefore it is necessary to fix the He, C and N abundance for the fit to some "reasonable" value. Our choice has been to use the He/C and O/C values derived from models of nucleo-synthesis in supernovae, and in particular the models of Johnston & Yahil (1984).
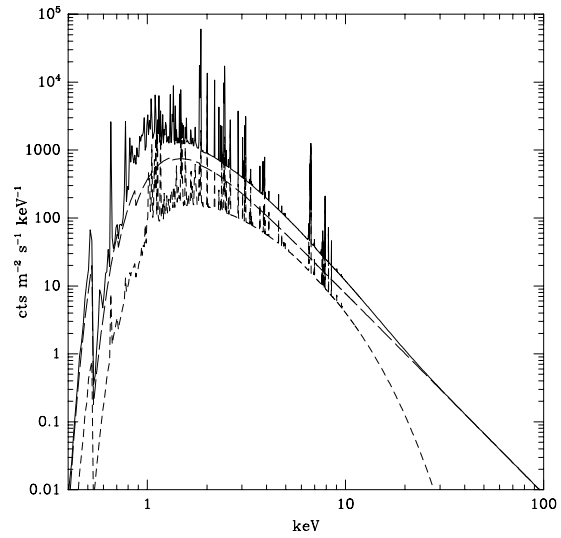

Fig. 2. The deconvolved broad-band BeppoSAX spectrum of Cas A, using the data from the LECS, MECS, HPGSPC and PDS, together with the individual contribution from the best-fit two-component NEI model and the power-law high energy tail.

For the CSM component, in addition to the normalization, the post-shock temperature and the ionization time, we have left the *global* abundance free to vary, i.e. we have assumed that the abundance ratios of elements heavier than N in the shocked CSM are well modeled by solar values. The abundance values of He and N were fixed to 10 times the solar value, an estimate in line with optical observations of the emission from the shocked CSM (Chevalier & Kirshner 1979). This implies a depletion of H in the CSM, so that the global abundance of the CSM is expected to be non-solar due the influence of the strong stellar wind in the late stages of the progenitor star's life.

3. Results

The two-component NEI plus power-law model discussed above provides a good fit to the observed spectrum across a broad range of energies, i.e. from 0.5 to 80 keV, as shown in Fig. 1. Given the high signal-to-noise ratio of the spectra used, the uncertainties are likely to be dominated by systematic effects, as for example uncertainties in the (relative) calibration of the various detectors. In particular there is some energy-dependent effective-area inconsistency between the LECS and MECS data (likely linked to the extended nature of the source), which is evident around the Fe K complex. Additionally, there is evidence for some residual features in the HPGSPC spectrum around $\simeq 12$ keV, which is likely to be due to residuals in the background subtraction.

The resulting χ^2 of the fit, at 1160 with 382 degrees of freedom is formally not acceptable. However, given the large residual systematics, the nominal χ^2 per se cannot be used as a measure of the acceptability of the model. The best-fit parameters are listed in Table 1, while the derived ejecta mass for each species is listed in Table 2.

While the fit supplies a good phenomenological description of the data some of the best fit parameters are rather peculiar. Most striking are the high Ni abundance and the zero Ne abundance. While Ne has been found to be under-abundant in the optical (Fesen 1990) and X-ray (VKB), the Ne-K lines fall in the same energy range where the rich Fe-L and Ni-L line complexes are, so that, at the limited energy resolution of non-dispersive spectrographs, it is difficult to disentangle real Ne abundance effects from, for example, modeling problems. The same applies to the Ni abundance, which is derived exclusively from the L-shell line complex, which is modeled, in SPEX, somewhat inconsistently with respect to the Fe-L complex.

4. The non-thermal tail

The separate contribution of the three components to the Cas A broad band X-ray spectrum is shown in Fig. 2. The power-law component dominates at the higher energies ($\gtrsim 20$ keV), but it also gives a sizable contribution to the continuum emission at the lower energies, being for example comparable in intensity to the thermal continuum near the Fe K complex. Such an additional continuum clearly influences the derived metal abundances, in particular making them higher with respect for example to VKB.

Possible explanations for the high-energy tail include (1) synchrotron radiation from shock-accelerated electrons with energies of several tens of TeV, similar to the model proposed for SN1006 (Koyama et al. 1995; Reynolds 1996); (2) non-thermal bremsstrahlung from electrons with energies of several tens of keV, which have just been accelerated from the tail of the thermal distribution, the so called injection spectrum; (3) an additional thermal component. Some of our results depend on the underlying assumptions. Modeling the tail as a power-law extending down to the lowest energies (as it was done here) is correct if the tail arises from a physically separate emission component such as synchrotron radiation. If the emission mechanism is however non-thermal bremsstrahlung the high energy photons arise from the non-maxwellian tail of the overall electron distribution, so that the power-law model will only be a good representation of the emission above $\simeq 15$ keV. In this case the best fit abundances would be too high and the estimated normalizations of the thermal bremsstrahlung too low. Furthermore, non-thermal electrons can also contribute to the line emission. Also, possible contribution of ^{44}Ti at 68 keV and 78 keV (Iyudin et al. 1994; The et al. 1996) to our last bin may alter our best fit model.

5. Discussion

The model for the X-ray emission of the Cas A remnant discussed here follows a similar approach to VKB, with the addition of a power-law component which dominates at the higher energies.

Some of the VKB ASCA SIS derived parameters are somewhat puzzling, specially when compared to predictions from theoretical models of nucleo-synthesis. For example, the ejecta appear to be quite deficient in their Ne and Mg abundances, with a mass fraction one order of magnitude lower than expected from nucleo-synthesis models (Johnston & Yahil 1984). The same is true for the Fe abundance, which again is lower by almost one order of magnitude.

Assuming that the power-law component (which was not used by VKB in their analysis) really is a physically separate component of the spectrum, it significantly influences the mass estimates for the ejecta, because of differences in the estimated abundances as well as in the emission measure. For most elements the derived abundance estimates relative to O increase, when the power-law component is added, by a factor of about 3, with the exception of Ne and Ni (as discussed above), with the mass estimates correspondingly decreasing by $\simeq 40\%$ with respect to an analysis using only the two NEI components. The apparent lack of Ne and Mg in the ejecta still stands. The swept-up mass decreases (with respect to VKB) from $\simeq 8\,M_\odot$ to $\simeq 5\,M_\odot$, while the ejecta mass decreases from $\simeq 4\,M_\odot$ to $\simeq 2\,M_\odot$. The lower derived ejecta mass does not alter the general conclusion of VKB that the progenitor of Cas A was a star of low mass (i.e. which had lost most of its mass).

Some of the assumptions made in the analysis are derived from a priori considerations about the physics of the remnant, and have therefore to be critically assessed. Changes in the assumption may lead to changes in the derived parameters. The two perhaps most critical assumptions are (1) the temperature structure of the thermal emission components and (2) the nature and thus precise spectral shape, specially at the lower energies, of the hard tail component. The consequence of these assumptions on the interpretation of the X-ray emission from the remnant will be examined in a future paper, in which we will also make use of spatially resolved spectroscopy in order to study if different components originate from distinct regions.

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